Electro-Thermo-Mechanical Modeling

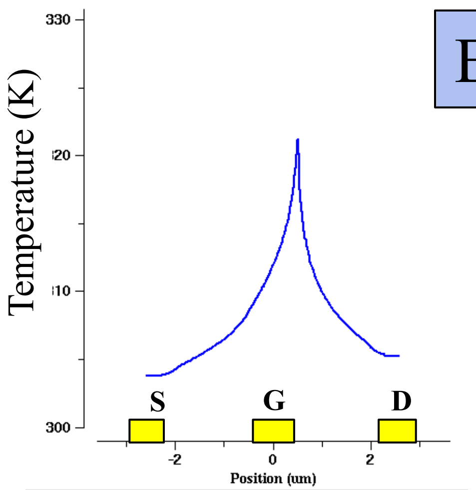
Erin Patrick, Mark Law

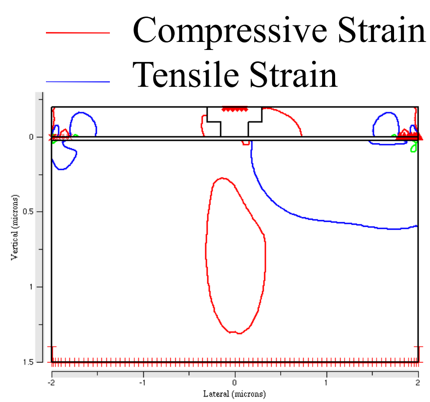
GATOR Engineering
UNIVERSITY OF FLORIDA

Code Development for Multiphysics Modeling

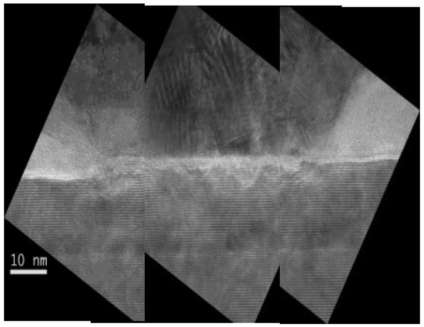
FLOORS

Electro-Thermo-Mechanical Modeling





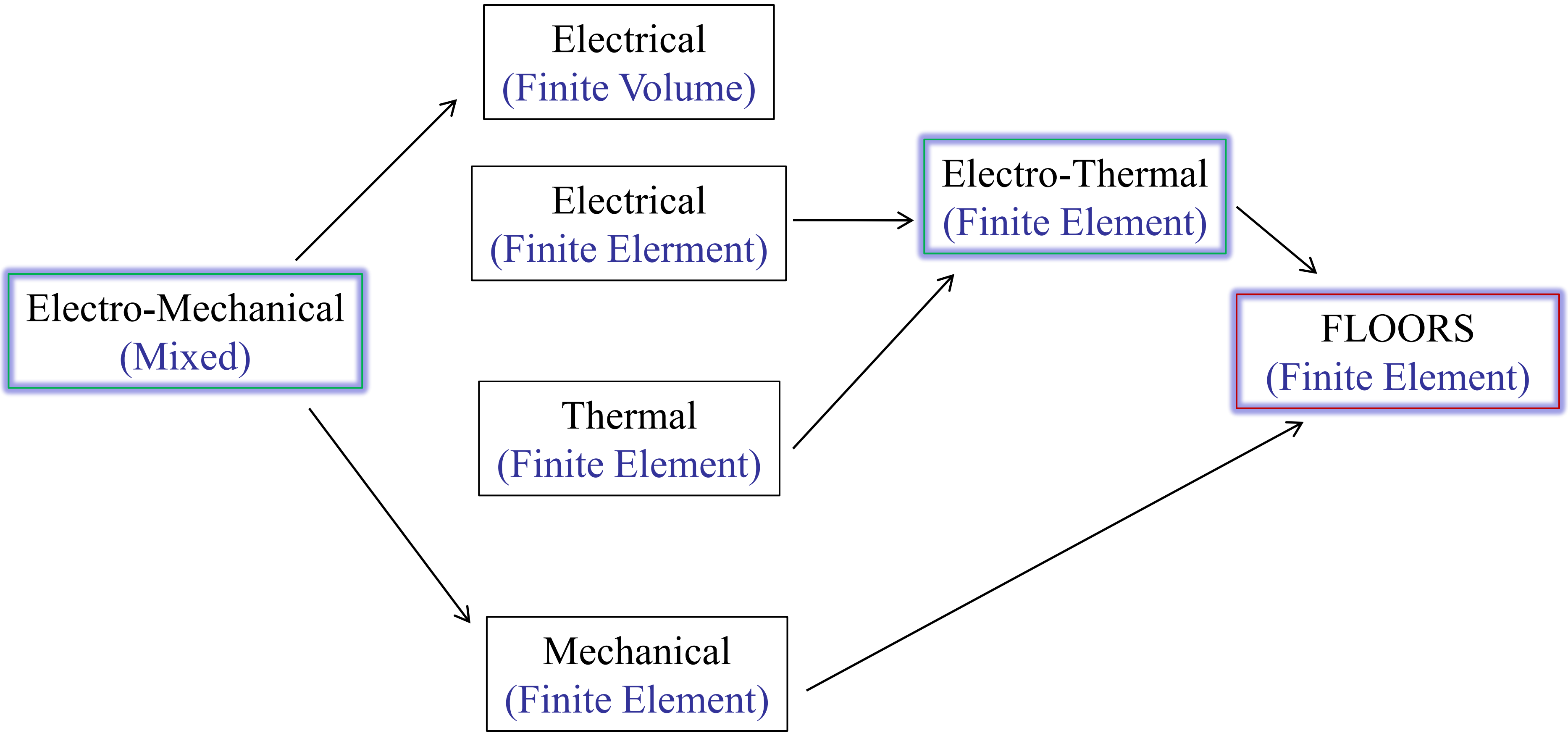
Defect Modeling ⟶ Device Performance Prediction



t=0, As Built

t>0, Degradation

Discretization Methods



Discretization – Current Density

Quasi-Fermi Current Density	Boltzmann Relations	Drift-Diffusion Current Density
$J_n = -q\mu_n n \nabla \phi_n$	$\phi_n \equiv \psi - \frac{kT}{q}\ln(n/n_i)$	$J_n = qn\mu_n \mathrm{E} + qD_n \nabla n$
$J_p = -q\mu_p p \nabla \phi_p$	$\phi_p \equiv \psi + \frac{kT}{q}\ln(p/n_i)$	$J_p = qp\mu_p \mathrm{E} - qD_p \nabla p$

- To obtain a closed system of equations, current densities written as function quasi-Fermi levels
- Using Boltzmann relations, current density can be written in the familiar relationship as the sum of drift and diffusion components
- Drift-Diffusion subtracting large numbers is not a good recipe with finite precision arithmetic

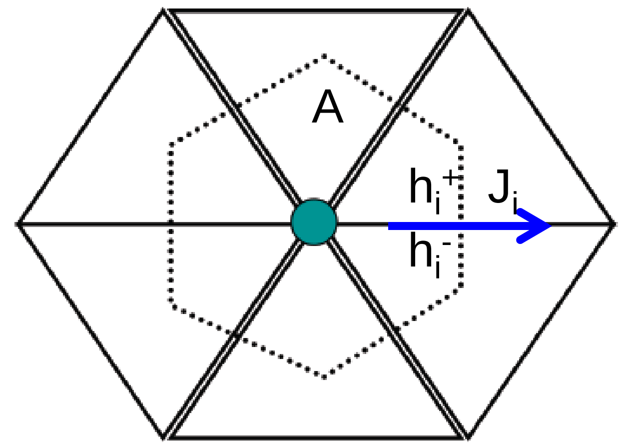
Dan Cummings, SISPAD

Finite Volume Scharfetter-Gummel (FVSG)

- Each PDE is integrated over a control volume *A*
- A is defined by the perpendicular bisectors of mesh elements
- PDE integrated using Green's formula
- Current $J_{n,p}$ evaluated using the Scharfetter-Gummel
- Scharfetter Gummel
  - Assume field and current constant
  - Solve resulting equation
  - $J_n/q = D\ (\ B(t)\ n_i+\ -\ B(-t)\ n_i-\ )\ /\ l_i$
  - $t = \mu\ E\ /\ D$
  - $B(t) = t\ /\ (e^t - 1)$ Bernoulli Function

$$J_n = qn\mu_n \mathrm{E} + qD_n \nabla n$$

$$\frac{dn}{dt} = \frac{1}{q} \nabla \cdot J_n - U_n$$



- Advantages:
  - Commonly used "proven" method
  - Assembly time, each edge assembled once
- Disadvantages
  - Current defined only on edges, not continuous in space
  - Impact Ionization, Joule Heating more difficult
  - Works best when grid is aligned with current flow

$$\frac{1}{q} \sum_i J_i \left(h_i^+ + h_i^-\right) - A\left(U_n + \frac{dn}{dt}\right) = 0$$

Dan Cummings, SISPAD

Finite Element Quasi-Fermi (FEQF)

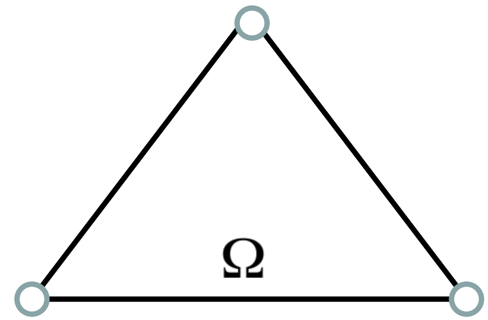
- $\phi_{n,p}$ defined at grid nodes
- Use shape function in an element
  - Piecewise linear most common
  - Can be higher order
- Integrate equations and minimize error

- Advantages:
  - Current is a continuous function over each element
  - Easier to compute Joule Heating, Impact Ionization
  - Compatible with strain calculations

- Disadvantages
  - Not as stable
  - Convergence issues

$$J_n = -q\mu_n n \nabla \varphi_n$$

$$\frac{dn}{dt} = \frac{1}{q}\nabla \cdot J_n - U_n$$



$$a(\psi, v) \equiv (-\rho, v)$$

$$a(\psi, v) \equiv \iint_{\Omega} \varepsilon \nabla \psi \cdot \nabla v \, dx\, dy$$

$$(-\rho, v) \equiv -\iint_{\Omega} \rho\, v\, dx\, dy$$

Electro-Thermo-Mechanical Simulation

	Poisson's Eq.	Electron/Hole Continuity Eq.
Electro:	$\nabla^2 \Psi = -\frac{q}{\varepsilon}(p - n + N_D - N_A)$	$\frac{dn}{dt} = \frac{1}{q}\nabla J_n$ $J_n = -q\mu_n n \nabla \phi_n$

Heat Eq.

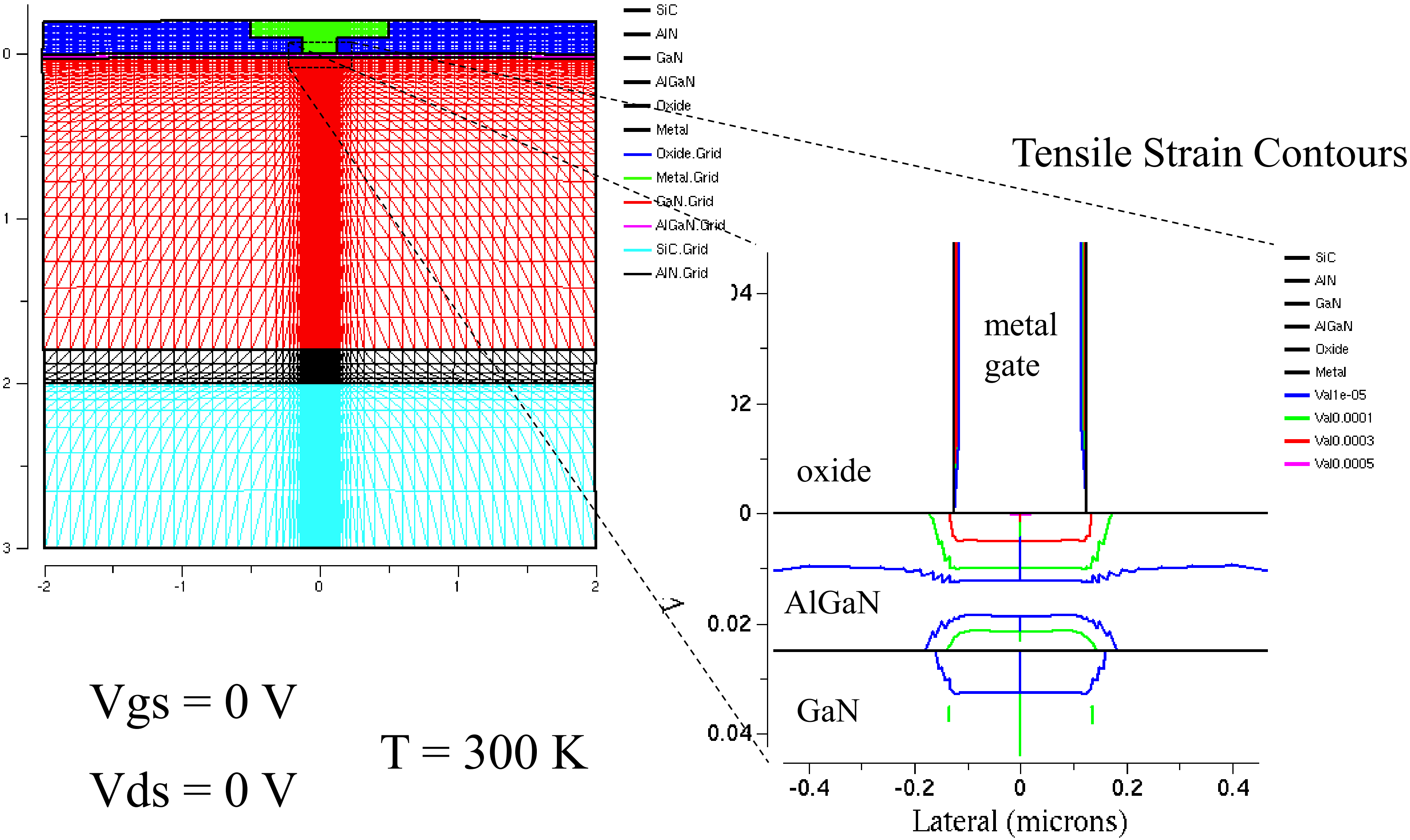
Thermo: $c\frac{\partial T}{\partial t} - \nabla \cdot K\nabla T = Q$ where, $Q = J_n^2 \frac{1}{q\mu_n n}$

Equilibrium Eq.

Mechanical: $\nabla \cdot \sigma + F = \rho \nabla^2 u$ where, $\sigma = D\,(\epsilon\text{-}\epsilon_0)$ $\quad D(T)$ function of temperature

$\epsilon = \nabla \Psi \cdot d_{pz}$

Simulation Results on GaN hemt - Baseline



Vgs = 0 V

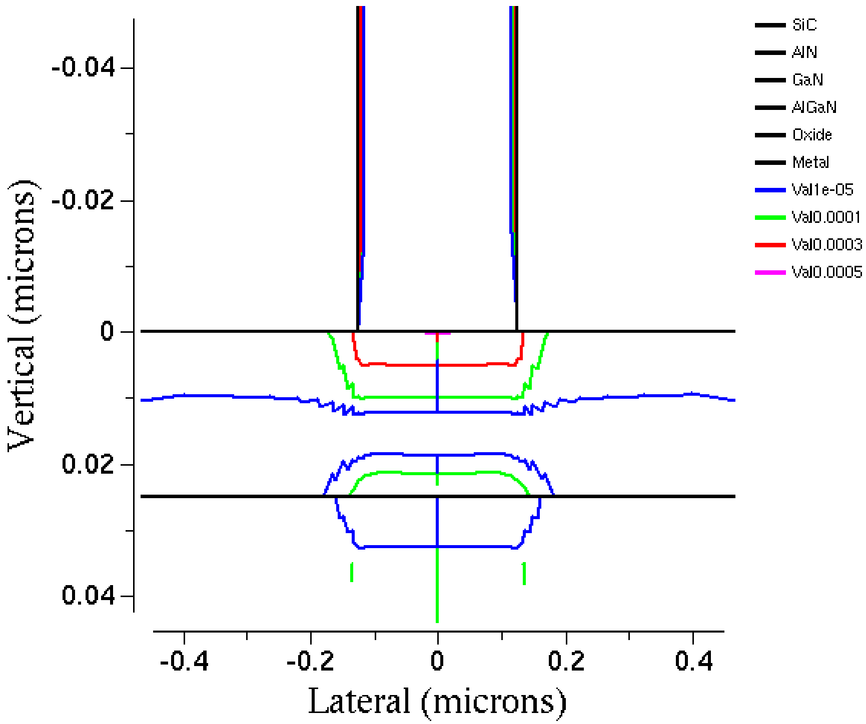
Vds = 0 V

T = 300 K

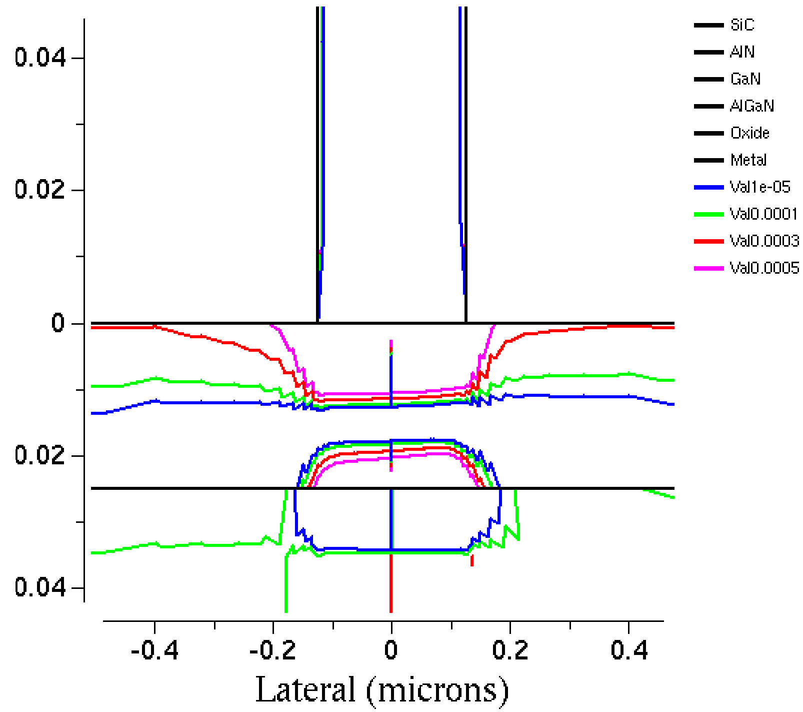
Inverse Piezoelectric Effect

No temperature dependence
on Young's modulus

Vgs = 0 V
Vds = 0 V
T = 300 K



Vgs = 0 V
Vds = 6.1 V
T(max) = 500 K

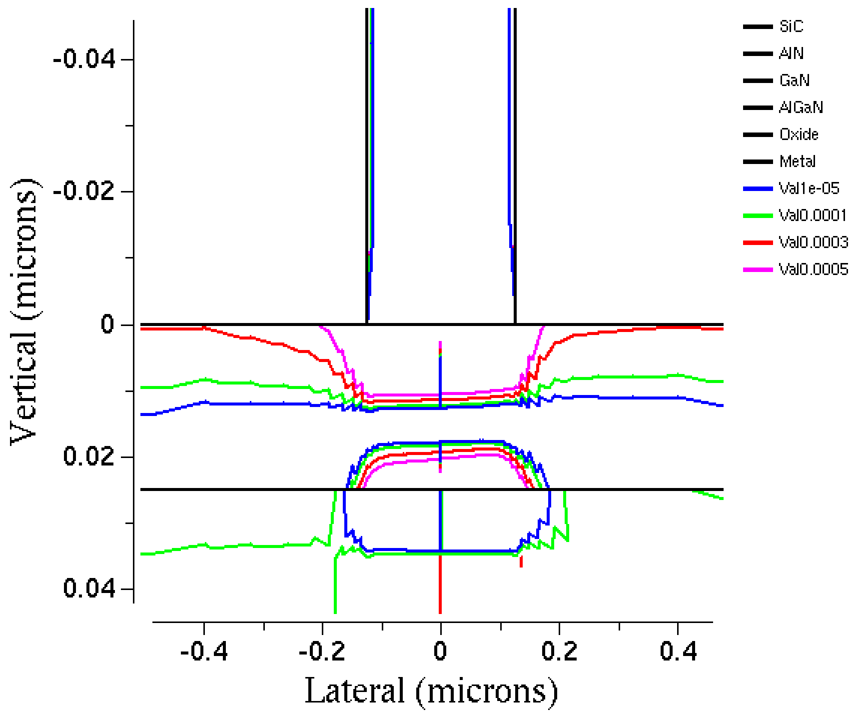


Temp dependence on Young's Mod.

No temperature dependence on Young's modulus

Vgs = 0 V   Vds = 6.1 V

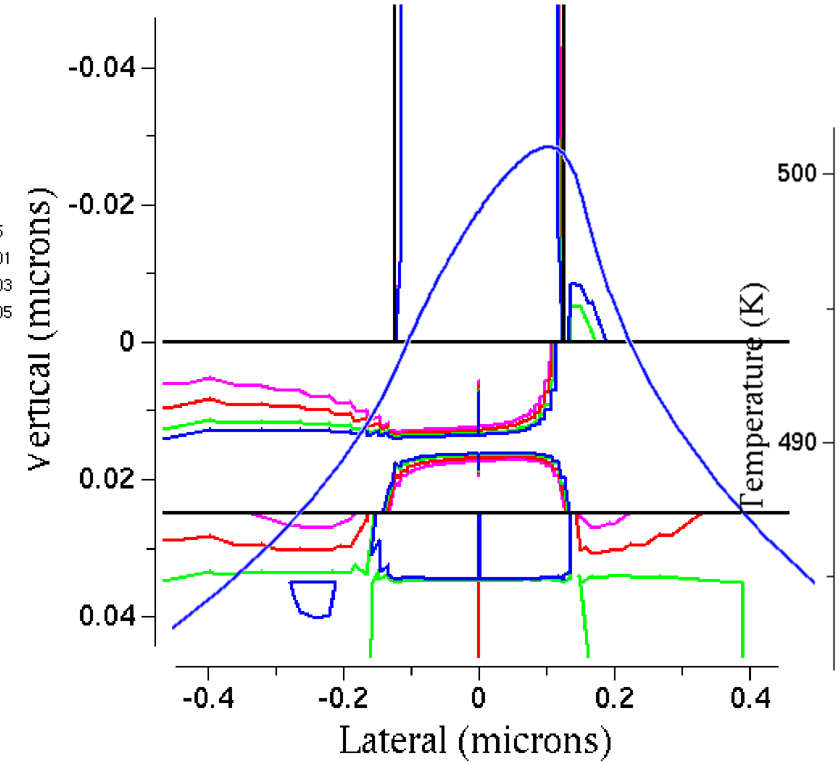
T(max) = 500 K



Temperature dependence on Young's modulus

Vgs = 0 V   Vds = 6.1 V

T(max) = 500 K



Summary and Future Work

- A finite element based simulator is needed for the the full electro-thermo-mechanical model
  - Couples mechanical strain with Joule heating and electrical operation
- Future Work
  - Incorporate David's work on Electromechanical degradation
  - Collaborate with Dr. Nishida's group to develop a model for gate leakage current